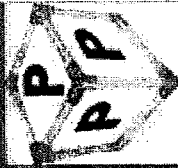


20" DR 21 PVC Pipe – Dorchester County, SC – 2200 foot RCP Crack

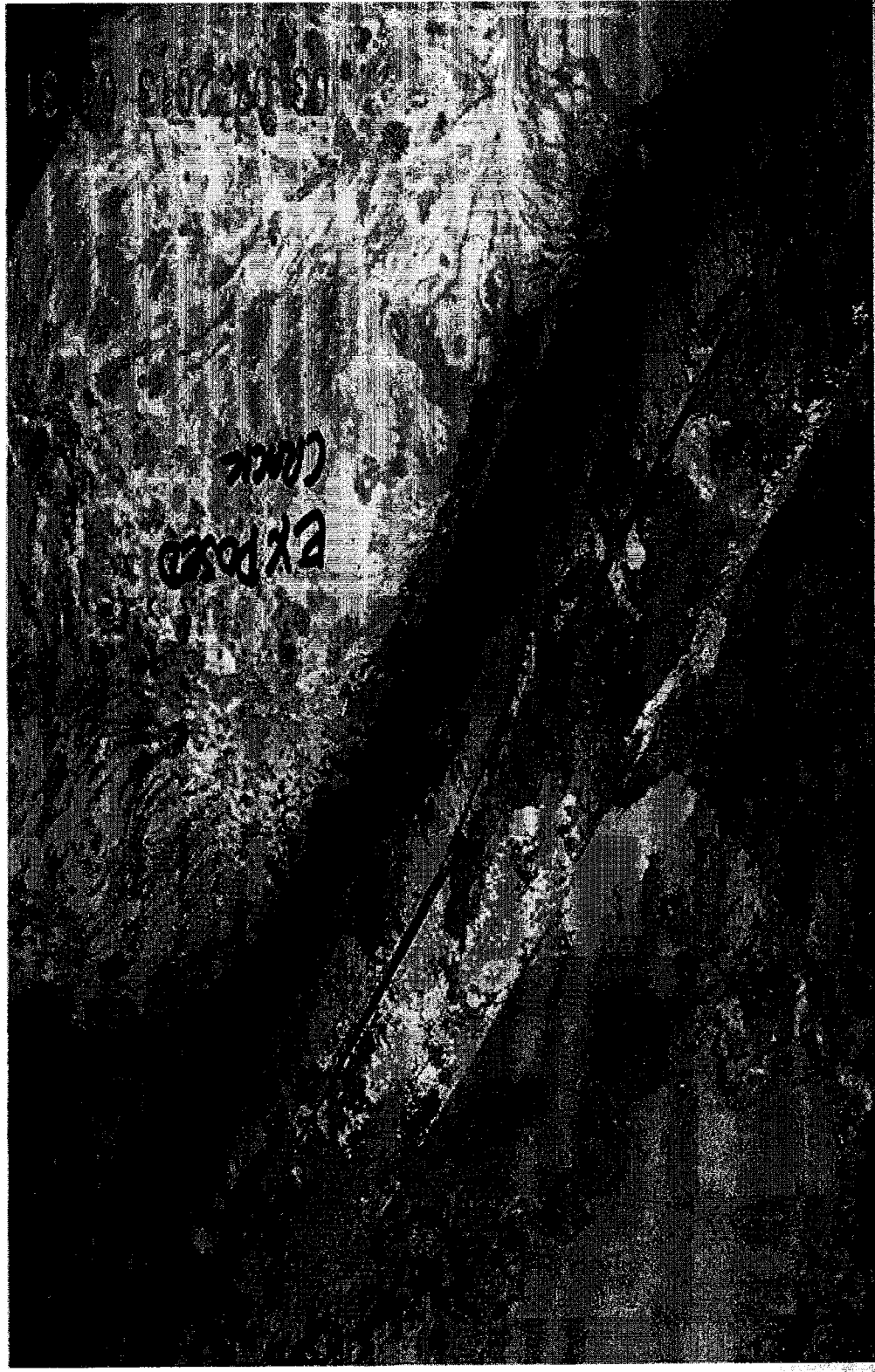


Salt Lake City, Utah

- Salt Lake City, Utah Water Company experienced RCP failures on two occasions.
- The first RCP failure occurred earlier this year when 16" DR 31 butt fused PVC pipe was being leak pressure tested – the crack ran 350 feet.
- They also had another RCP failure when they were cleaning this pipe. The crack ran 3300 feet. This is the longest known RCP failure in butt fused PVC pipe. They will replace all 13 miles of fused PVC pipe.



16" DR 21 PVC Pipe – Watford City, ND – 850 foot RCP Crack – in service failure



OUTLINE

RCP Failures in Butt Fused PVC Pipe

- Known RCP Field Failures in Butt Fused PVC Pipe
- RCP Laboratory Data for PVC Pipe
- Proposals to Prevent RCP Failures in FPVC

Butt Fusion Failures in PVC Pipe

- Known Butt Fusion Field Failures in PVC Pipe
- Joint Integrity Laboratory Data for PVC Pipe
- Proposals to Prevent BF Failures in FPVC



Rapid Crack Propagation (RCP)

- RCP is a material failure mode in which a crack propagates very rapidly over long distances.
- For RCP to occur there must be an initiating event such as a field induced crack.
- Specialized research on RCP began during WWII to address rapid cracking of continuously welded steel ship hulls.
- Considerable RCP research has recently been conducted in Europe on several plastic pipe materials (HDPE, MDPE, PVC, PA11, PA12) to determine the critical pressure.



Critical Pressure (P_c)

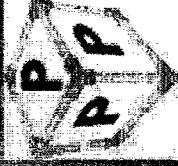
- The Critical Pressure (P_c) is the pressure above which RCP can be sustained. As long as G (driving force) is greater than G_D (material's dynamic fracture resistance) the crack will continue to propagate.
- HDPE is a ductile, semi-crystalline plastic material and not very susceptible to RCP – $G_D \sim 3.45 \text{ kJ/m}^2$ measured on PE*.
- PVC is an amorphous plastic material that is more susceptible to crack initiation – $G_D \sim 0.64 \text{ kJ/m}^2$ measured on PVCu*.

*E.J. Gurnahelds and P.S. Leewers (1993), "Rapid Crack Propagation in Plastic Water Pipes: Measurement of Dynamic Fracture Resistance," International Journal of Fracture, Vol. 79, Kluwer Academic Publishers, Dordrecht.

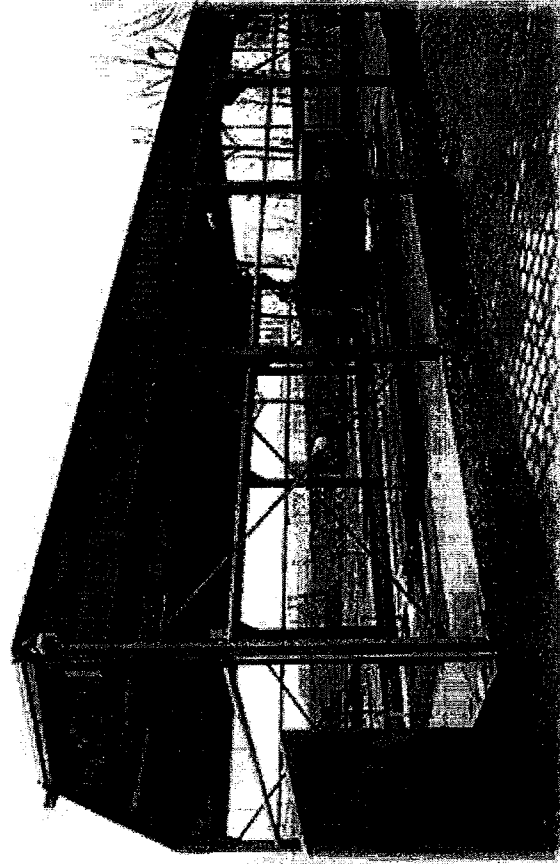
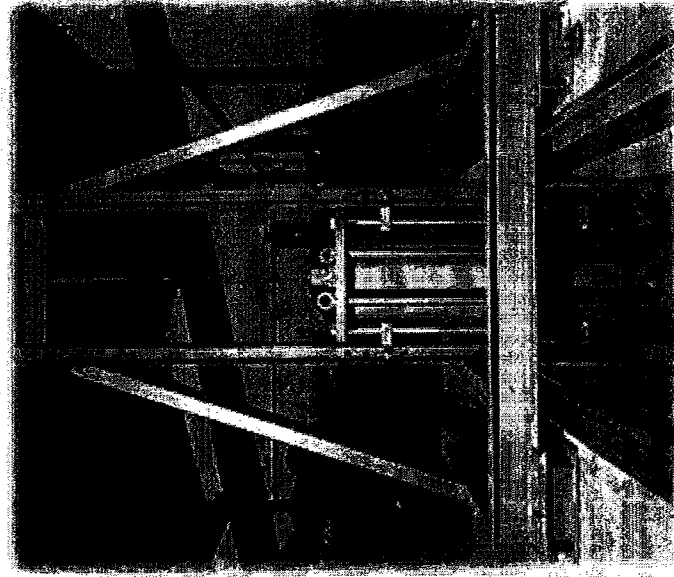


Test Methods to Determine P_c

- Full Scale (FS) test method is described in ISO 13478.
- Method requires a minimum of 50 ft of plastic pipe for each data point.
- Can be expensive and time consuming.
- Dr. Pat Leevers of Imperial College developed the Small-Scale Steady State (S4) test method.
- Test Method described in ISO 13477
- Uses much smaller pipe samples
- S4 results can be converted to FS results by using a correlation factor



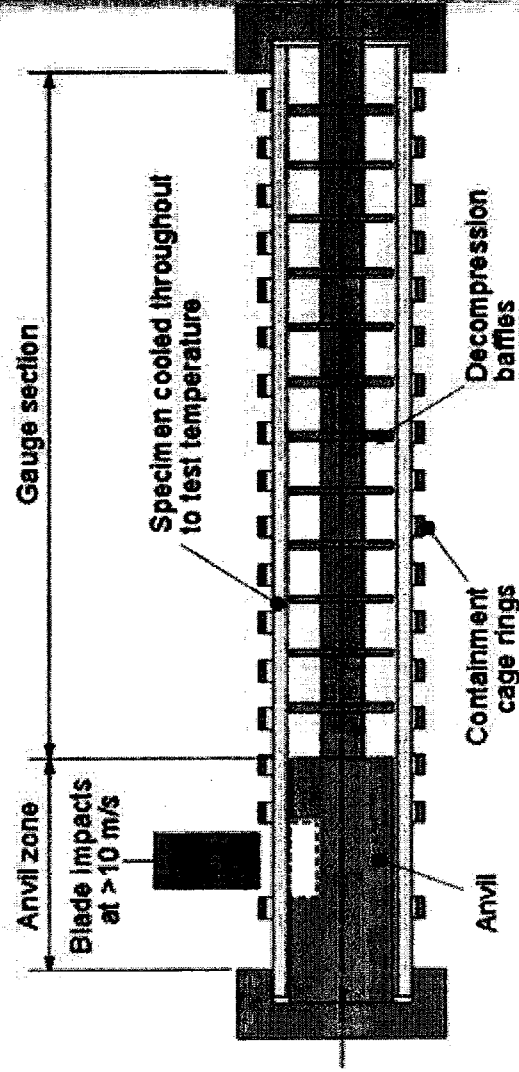
Full Scale Test, ISO 13478



**Becetel Research
Center Ghent
Belgium**



S4 Test, ISO 13477

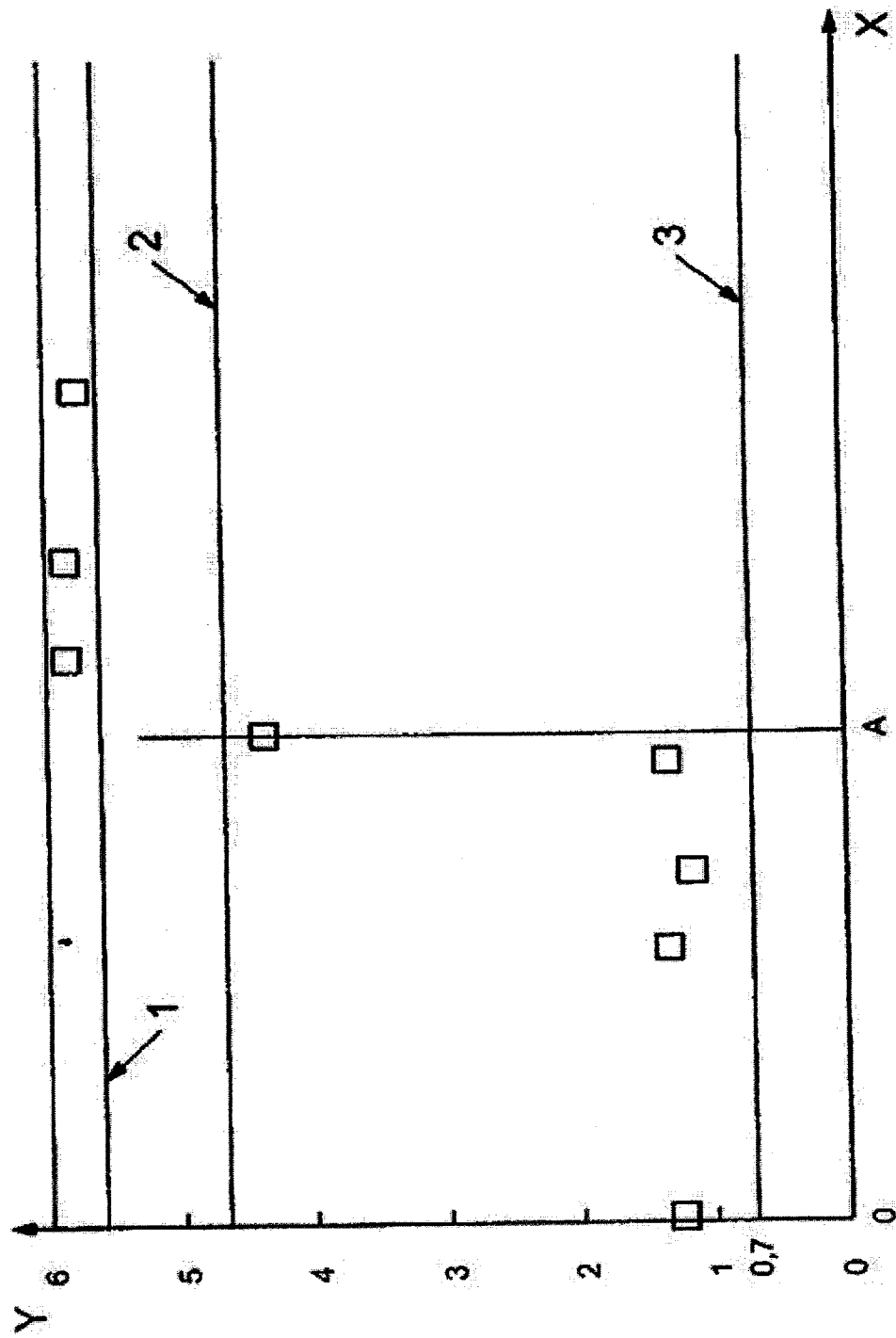


**Chevron Phillips Chemical Company,
LLC**

**Research and Technology Center
Bartlesville, OK**



ISO 13477 S4 Critical Pressure

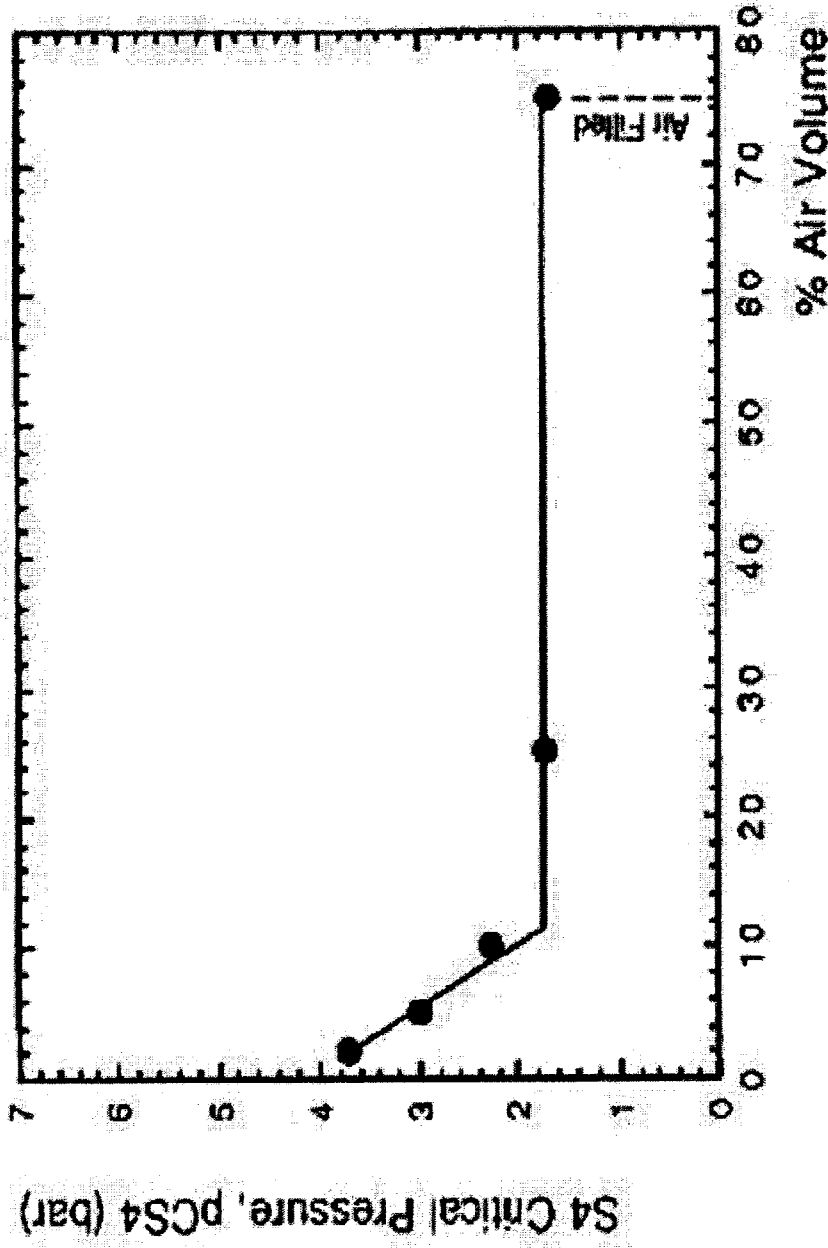


S4/FS Correlation Equation

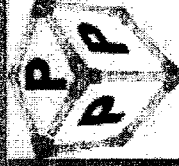
- The S4 test uses smaller pipe samples and a series of baffles. Interior baffles serve to impede de-pressurization
- Due to these baffles, pressure data from the S4 test are converted to Full Scale pressures using a correlation factor.
 - $P_{C,FS} = 3.6 P_{C,S4} + 2.6$ bar per ISO 13477
- The ISO correlation factor is conservative and material suppliers may develop their own correlation between S4 and Full Scale.



S4 Critical Pressure -PVC*



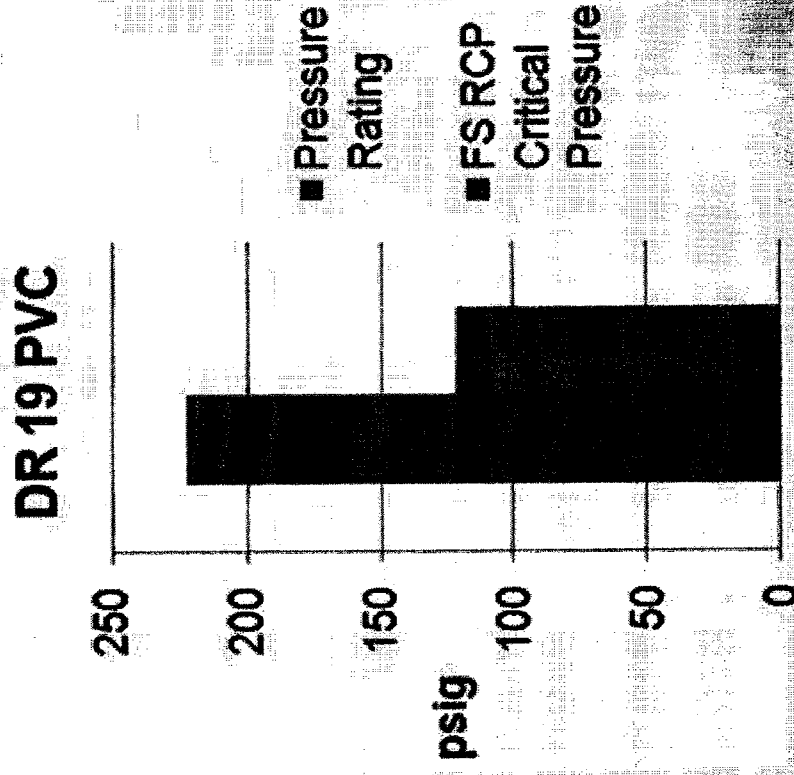
*C.J. Greenshields and P.S. Leavers, "The effect of air pockets on rapid crack propagation in PVC and PE water pipe" Plastic Rubber and Composites Processing and Applications, 24 (1986)



Critical Pressure v Pressure Rating for PVC

- $P_{C,S4} = 1.6$ bar for DR 19 PVC pipe with $\geq 10\%$ air*
- $P_{C,FS} = 3.6 P_{C,S4} + 2.6$ bar (ISO 13477 Correlation Equation)
- $P_{C,FS} = 8.36$ bar = 121 psig (1100 psi)

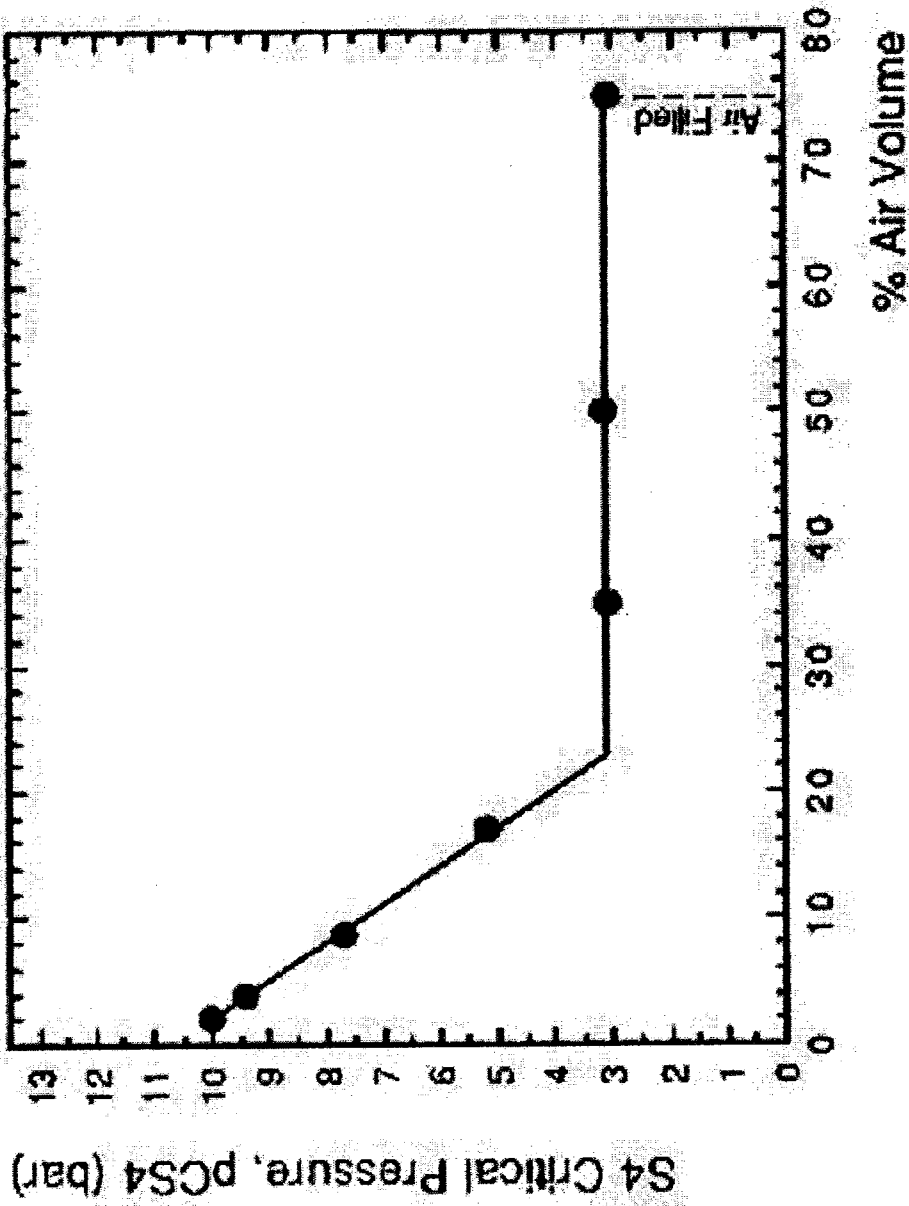
For DR 19 PVC pipe, the corresponding HDB-based pressure rating is 222 psig



*C.J. Greenshields and P.S. Leevers, 'The effect of air pockets on rapid crack propagation in PVC and PE water pipe', Plastic Rubber and Composites Processing and Applications, 24 (1995)



S4 Critical Pressure - PE



RCP Test Data for PE Pipe

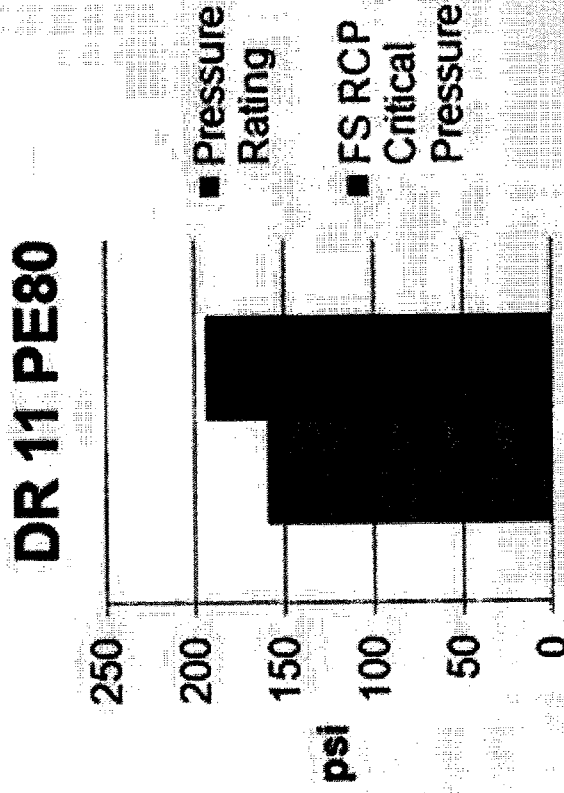
- $P_{C,S4} = 3$ bar for DR 11 PE80 at 3° C with $\geq 20\%$ air*.

- $P_{C,FS} = 3.6 P_{C,S4} + 2.6$ bar (ISO 13477 Correlation)

- $P_{C,FS} = 13.4$ bar (194 psig) for this DR 11 PE80

- Note that $P_C > PR$

PR = 160 psig for DR 11



*C.J. Greenshields and P.S. Leavers, 'The effect of air pockets on rapid crack propagation in PVC and PE water pipe', Plastics, Rubber and Composites Processing and Applications 24 (1993)



Pressure Rating – DR 11

New PE 4710 Pipe

$$\begin{aligned} 1) \text{ PR} &= 2 (\text{HDB}) (\text{DF}) / (\text{DR} - 1) \\ &= 2 (1600 \text{ psi}) (0.63) / (11 - 1) \\ \text{PR} &= 200 \text{ psig} \end{aligned}$$

2) S4 RCP Critical Pressure > 10 bar
 $P_{C,FS} > 560 \text{ psig}$ for DR 11

The pressure rating of 200 psig for DR 11 PE 4710 pipe is considerably lower than the full scale critical pressure, so RCP is never an issue for PE 4710 pipe.



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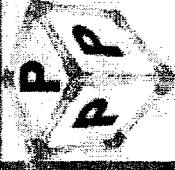
Butt Fusion Failures in PVC Pipe

- Known Butt Fusion Field Failures in PVC Pipe
- Joint Integrity Laboratory Data for PVC Pipe
- Proposals to Prevent BF Failures in FPVC



Actual Field Experience – Chatham, IL

- Butt fused 18" DR 25 PVC pipe was held at a pressure of 60 psig for a couple days – no reported problems.
- Based on S4 RCP data and the S4/FS correlation factor, the RCP full-scale critical pressure for DR 25 PVC pipe is 92 psig.
- When the pressure for this 18" DR 25 PVC pipe was increased for the leak pressure test, an RCP event occurred when the pressure reached 100 psig. The crack ran 850 feet. The pressure rating for this pipe is 170 psig.



Actual Field Experience – Dorchester County, SC

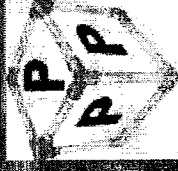
- Butt fused 20" DR 21 PVC pipe was held at a pressure of 90 psig for a couple days – no reported problems.
- Based on S4 RCP data and the S4/FS correlation factor, the RCP full-scale critical pressure for DR 21 PVC pipe is 110 psig.
- When the pressure for this 20" DR 21 PVC pipe was increased for the leak pressure test, RCP occurred when the pressure reached 130 psig. The crack ran 2200 feet. The pressure rating for this pipe is 200 psig, which is well above the pressure where RCP actually occurred.



Dimension Ratio (DR)

- *“Although it is difficult to estimate the maximum crack speed for a particular material, experimental data from transducer measurements give 600 m/sec for PVC and 300 m/sec for PE at 3° C just above the critical pressure. These wave speed values correspond to a minimum DR 13 for PVC and DR 29 for PE. Although such high DR's are rarely seen in PE, almost all PVC pipe is 'thin-walled' (at least higher than DR 13) and as such is capable of sustaining RCP in 100 percent water pressurized pipe.”*

Ref: Greenshields and Leevers



How to Design to Prevent Rapid Crack Propagation

- To prevent long running cracks due to RCP in PVC pipe, the water design engineer should:
 - 1) lower the pressure rating (PR) of the pipe to $PR < P_{c,FS}$. Need to determine $P_{c,FS}$ for PVC pipe.
 - 2) use thicker wall pipe (lower DR for given pipe size) – DR 13 pipe or lower
- To prevent long running cracks due to RCP in PE pipe, the water design engineer should:
 - 1) use DR 29 pipe or lower, or
 - 2) use high performance PE 4710 material with a high $P_{c,FS}$

